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QUARTERMASTER RESEARCH & ENGINEERING COMMAND
U S ARMY

TECHNICAL REPORT
QMRE-14

FC

INVESTIGATION OF BALLISTIC PROTECTION MATERIALS FOR PERSONNEL BODY ARMOR

PROGRESS REPORT I

QUARTERMASTER RESEARCH & ENGINEERING CENTER
CHEMICALS & PLASTICS DIVISION
MECHANICAL ENGINEERING DIVISION
TEXTILE, CLOTHING & FOOTWEAR DIVISION

DECEMBER 1957 NATICK, MASSACHUSETTS

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HEADQUARTERS
QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
OFFICE OF THE COMMANDING GENERAL
NATICK, MASSACHUSETTS

Major General Andrew T. McNamara
The Quartermaster General
Washington 25, D. C.

Dear General McNamara:

This report, "Investigation of Ballistic Protective Materials for Personnel Armor," is the first in a series presenting energy absorption data and ballistic limits for a number of materials. The investigation is expected to provide information on the design of composite armor that will combine the protective qualities of all materials used in the armor structure.

This study reveals that the missile retarding and stopping properties of those materials tested varies with the type of materials and with the velocity and size of the impacting missile. Moreover, it has been found that combinations of materials properly positioned in the armor structure can provide greater ballistic protection per unit weight than any single material contained in the composite armor.

Sincerely yours,

C. G. Calloway
C. G. CALLOWAY
Major General, USA
Commanding

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Quartermaster Research & Engineering Center
Natick, Massachusetts

CHEMICALS & PLASTICS DIVISION
MECHANICAL ENGINEERING DIVISION
TEXTILE, CLOTHING & FOOTWEAR DIVISION

Technical Report

QMRE-14

INVESTIGATION OF BALLISTIC PROTECTIVE MATERIALS FOR PERSONNEL ARMOR

Progress Report I: Energy Absorption and Ballistic Resistance Limits (V_{50}) of Armor Materials when Perforated by a Fragment Simulating Missile (.22 Caliber T37)

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Project Reference:
7-80-05-001

December 1957

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FOREWORD

The recognized efficacy of armor, as demonstrated by the metal helmet in World War I, by flyers' armor in World War II, and by the armor vest in Korea, does not obviate the need for providing protection to the combat soldier against battlefield missiles of size, velocity and shape different from those which can be defeated by present armor. Greater protection by armor, equivalent to rendering less effective the anti-personnel weapons of the enemy, will result in saving additional lives and avoiding or minimizing of injuries, with consequent maintenance of the combat force.

Exploratory work (QMR&E Command Technical Report CP-5) has shown that the development of armor providing a greater degree of protection seems possible through the use of armor constructions consisting of two or more component materials. Several composites of two components were found to have V_{50} ballistic resistance limits greater than that of either component of equal areal density. The basis suggested for selection of materials and their order in the armor structure is that the most effective retardation material be used throughout the missile velocity range, as the missile passes from the front to the rear of the armor. Data showing the effectiveness of materials over a wide range of missile striking velocities and for a variety of battlefield missiles (or missile simulators) are obviously required before armor constructions can be designed with high protection/weight ratios.

This is the first report in a series intended to present energy absorption data and ballistic resistance limits (V_{50}) for a variety of materials. Publication of these data will be made at frequent intervals, even though the phase being investigated may not have been completed, in order to reduce the delay in making data available to other Government activities interested in armoring men and equipment. It is hoped that early release of the data obtained will benefit other laboratories conducting research and development on armor, will assist in avoiding undesirable duplication of effort, and will inform the armor-using agencies of what might be expected in the future.

Approved:

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CONTENTS

ABSTRACT

This report is the first in a series presenting energy absorption data and ballistic resistance limits (V_{50}) for a variety of materials. These data are expected to be useful in designing composite personnel armor, consisting of two or more dissimilar components, that will have a better protection/weight ratio than single-material armor. This report presents data obtained with the .22 caliber, 17 grain T37 fragment simulating projectile for nine materials (nylon batting, nylon fabric, Doron (a glass fabric, polyester resin laminate), glass, polymethyl methacrylate, aluminum alloys 2024-T3 and 2024-T4, titanium alloys A-110AT and Ti-140A, AISI 301 corrosion resisting steel and Hadfield steel).

The data show that these materials differ markedly in the ability both to stop missiles and to retard penetrating missiles. The energy lost by penetrating missiles divided by the areal (surface) density of the material was found to be velocity-dependent for all materials. The relationships between materials also changed with missile striking velocity.

INVESTIGATION OF BALLISTIC PROTECTIVE MATERIALS FOR PERSONNEL ARMOR

INTRODUCTION

Armor worn by the soldier has, generally, consisted of a single protective material. When more than one material has been used, the reason has been one of convenience or one of utilizing a specific property not obtainable with the material chosen specifically for its protective characteristics. For example, the non-protective functions required of the metal helmet shell and plastic helmet liner, when used separately, have led to the use of two dissimilar materials. Another example is that of the combination of overlapping metal plates backed by nylon fabric used in World War II flyer's armor. In this case, the comfort of fabric was preferred to the discomfort of metal.

Within the last twelve years, several investigators have proposed and demonstrated that certain specific combinations of materials possess a higher ballistic resistance limit or missile-stopping ability than single material armor of equal weight per unit area. Webster(1) in 1945, on the basis of his experiments, calculated that a glass-Doron combination was superior to either component and to Hadfield steel as well, in providing protection against small arms fire. In 1953, Weinberger and Delcellier(2) reported that the ballistic resistance of fabric armor could be increased by a combination of fabrics which took maximum advantage of each fabric's behavior at different velocity levels. A practical application of this finding was the use of both nylon and Fortisan fabrics in the Canadian armor vest. Also, in 1953, Weiner(3) reported that an improvement in ballistic resistance limit was obtained by selecting, for the front layers of a fabric armor structure, a fabric highly resistant to shear and, for the rear layers, a fabric of high resistance to yarn slippage. In 1955-1956, Alesi(4) proposed and demonstrated, with titanium-nylon fabric and polymethyl methacrylate-polyvinyl butyral composites, that armor consisting of dissimilar materials has greater ballistic resistance than any one component material of equal weight per unit area, provided the component materials are properly chosen and positioned in the armor assembly with respect to the direction of missile approach. The components in the front portion of the armor are selected from materials effective in reducing the velocity of the missile and the rear components are chosen from materials effective in stopping missiles. In this armor design, each component opposes the missile in the velocity range in which it is most effective in retarding (and ultimately stopping) the missile.

Energy absorption (missile velocity loss) data for various materials tested with a variety of battlefield missiles or missile simulators over a wide range of striking velocities are being determined at the QM R&E Center to permit the design of improved composite armor. This report is one of a series presenting energy absorption and ballistic resistance (V_{50} limits) data obtained on single materials and composites. Data will be presented in the series for tests conducted with caliber .10, .15, and .22 fragment simulating projectiles, flechettes (one or more type or weight, depending upon availability) and low-weight missiles of regular geometric configuration (spheres and cubes). Tests will be conducted at velocities up to at least 4,000 feet per second. Materials will be tested in the range of areal densities suitable for personnel armor, viz., 10 to 40 ounces per square foot. This report presents energy absorption data and V_{50} ballistic resistance limits determined with the .22 caliber T37 fragment simulating projectile for nine materials tested singly. This group of materials includes metals, plastics, textiles and glass.

MATERIALS TESTED

The materials for which data are presented in this report are listed in Table I.

TABLE I. Thickness and Areal Density of Materials Tested

Material	Nominal Thickness (inches)	Nominal Areal Density (oz. per sq. ft.)
Nylon Armor Fabric	(3, 6 & 12 layers)	4.8, 9.6 & 19.2
Nylon Batting	-	6.4 and 13.1
Doron	1/8	19.2 and 21.1
Window Glass	1/8	23.3 - 26.0
Plexiglas II - UVA	1/4	24.0 - 24.7
Titanium Alloy A-110 AT	0.063	24.0
Titanium Alloy Ti-140 A	0.064	24.5
Aluminum Alloy 2024 - T3	1/8	29.0
Aluminum Alloy 2024 - T4	1/4	57.0
AISI 301 Corrosion Resisting Steel	0.040	25.7 - 26.3
Hadfield Steel	0.063	37.9 - 40.0

A description of these materials is given in the following section. Properties for some of these materials as established by specifications, industry standards or by actual tests are given in Appendix A.

Nylon Armor Fabric

The nylon armor fabric tested is a standard nylon armor fabric procured by the Quartermaster Corps under Military Specification MIL-C-12369(A) (QMC), 31 January 1955.

The fabric construction is a 2 by 2 basket weave with two ends weaving as one and two picks weaving as one. The warp and filling yarns consist of five plies of 210 denier 34-filament nylon finished together with 3 to 4 turns per inch. The fibers are a high tenacity, bright filament, nylon 66 (polyhexamethylene adipamide).

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The physical characteristics of the fabrics are given below. (Data from MIL-C-12369A).

Weight per Square Yard (oz.)	Yarns per Inch		Breaking Strength (lbs.)		Ultimate Elongation (%)	
	Warp	Filling	Warp	Filling	Warp	Filling
14.0	46	40	850	775	25	20

Nylon Batting

The nylon batting tested is an experimental product of the E. I. duPont de Nemours Company, Inc. This is a non-woven, nylon filament structure prepared as a needled batt. This product is identified as "nylon non-woven ballistic batt (candidate for helmet liner)." It was tested in areal densities of 6.4 and 13.1 ounces per square foot.

Doron

Doron is the name given to glass fabric-laminate armor developed by the Quartermaster Corps during World War II. At present, it refers to a specific uni-directional glass fabric cross-laminated with a thermo-setting, unsaturated polyester type resin. A description of this type of armor material is given by specification MIL-I-17368 (MC) Insert, Body Armor. Doron of 1/8-inch nominal thickness from two sources was tested since sufficient material from one source was not available. One was manufactured by the Continental Diamond Fibre Company and designated grade GB - AL. The other was flat plates taken from armored clothing believed to have been produced in 1950.

Glass

Window glass, obtained from replacement stocks at the QM R&E Command, was tested in a nominal thickness of 1/8 inch.

Polymethyl Methacrylate

Plexiglas II - UVA, a heat resistant grade of cast acrylic sheet with good resistance to ultra-violet radiation, manufactured by Rohm and Haas Co., was tested in a nominal thickness of 1/4 inch.

Titanium Alloy A-110AT

Titanium Alloy A-110AT is a single-phase, so-called alpha-type alloy having relatively high strength at elevated temperatures, with excellent welding characteristics. It represents the first commercial production of a titanium alloy containing an appreciable quantity of tin and was developed primarily for aircraft structural applications. The A-110AT alloy also combines toughness, excellent fatigue strength and high creep strength at elevated temperatures, with machinability.

Titanium A-110AT (Heat No. D1-214530) was procured from Rem-Cru Titanium, Inc., Midland, Pa. by the McCord Corp., Detroit, Michigan for helmet-forming evaluations under Contract DA19-129-QM-151, New Metallic Alloys for Helmet Applications. It was procured to McCord Corp. specifications rather than to MIL-T-009046(ASG). The thickness was 0.063 inch, the density 0.161 lbs. per cubic inch, and the material was in the annealed condition.

Titanium Alloy Ti-140A

Titanium alloy Ti-140A is a two-phase, so-called "alpha-beta type alloy having relatively high strength in the annealed condition, high temperature stability and good impact resistance. Following the usual pattern in titanium alloy development, this alloy is primarily of interest for aircraft. Ballistic interest was based on potentially good ballistic and drawing (helmet) characteristics. Helmet drawing evaluations, to date, have not confirmed predicted good drawability.

Titanium Ti-140A (Heat No. M3073) was procured from Titanium Metals Corp., New York, New York, by the Bureau of Ordnance, Navy Department. Chemical analysis and mechanical property tests were performed by the Naval Gun Factory. (See Appendix A.) It was furnished to the McCord Corp., Detroit, Michigan for helmet forming evaluations under Contract DA19-129-QM-151, New Metallic Alloys for Helmet Applications. The thickness was approximately 0.060 inch, the density 0.169 lbs. per cubic inch, and the material was in the annealed condition.

Aluminum Alloy 2024-T4

Aluminum alloy 2024-T4 is classified as a high-strength wrought alloy and, as such, is used extensively in aircraft and other structural applications. In sheet form, tensile strength and elongation are about equal in the transverse and longitudinal directions. It is a heat-treatable alloy and, in this case, has been heat treated to obtain the T4 temper (solution heat treated and naturally aged to a substantially stable condition). The numeral "4" indicates that the product has either not been cold worked after heat treatment or applicable specifications do not recognize the effect of cold work in flattening or straightening operations after heat treatment.

This material was procured from the U. S. Army Ordnance Arsenal, Watertown, Massachusetts for range calibration purposes. The thickness was 0.250 inch and the density 0.100 lbs. per cubic inch. While manufacturer and heat are not known in this case, it is understood the material meets the requirements of Specification QQ-A-355. (See Appendix A.)

Aluminum Alloy 2024-T3

The major difference between the 2024-T4 and 2024-T3 alloys involves processing after heat treatment. The T3 temper (solution heat treatment and cold worked) applies to products that are cold worked to increase strength or to products such as sheet, in which the effect on mechanical properties of straightening or flattening after heat treatment is recognized in specifications.

This material was procured from the U. S. Army Ordnance Arsenal, Watertown, Massachusetts for range calibration purposes. The density was 0.100 lbs. per cubic inch and the thickness 0.125 inch. While manufacturer and heat are not known, this material is understood to meet the requirements of Specification QQ-A-355. (See Appendix A.)

AISI 301 Corrosion Resisting Steel

AISI 301 corrosion resisting steel is a chromium-nickel, austenitic type. It is non-magnetic, highly ductile and may be subjected to severe forming and drawing operations. In the annealed condition, it has large capacity for cold work and is similar in this respect to Hadfield steel. The AISI 301 type is a standard stainless grade for structural applications as it combines maximum strength and excellent workability with other desirable characteristics. Strength is not increased by heat treatment, but may be increased from approximately 90,000 PSI to 185,000 PSI by cold working.

The AISI 301 steel used for these tests was procured by Comstock and Wescott, Inc., Cambridge, Mass. for use in Contract DA19-129-QM-620, Development of Metallic Personnel Armor Materials and Components. It was purchased commercially rather than to Specification QQ-S-00766 (Navy Bureau of Ships); the heat is not known. The thickness was 0.040 inch, density 0.290 lbs. per cubic inch and the material was in the annealed condition.

Hadfield Steel

Austenitic managanese steel, also called Hadfield steel after its inventor, is an extremely tough, non-magnetic steel alloy characterized by relatively high strength, high ductility, large capacity for work hardening and excellent wear resistance. A work hardening capacity from about Rockwell B90 (annealed) to Rockwell C52 is reported. As rolled or as cast material, it is normally given a "toughening" (annealing) treatment by heating to approximately 1850°F and quenching in water. It is interesting to note that heating annealed or work-hardened material above approximately 500°F will cause embrittlement and impairment of desired mechanical properties. The properties of Hadfield steel are applicable where high shock resistance, toughness and absorption of energy are required at relatively low velocities. For this reason, Hadfield steel is extensively used in such industries as construction, mining, quarrying, dredging, and railroading, where it is incorporated in rock crushers, grinding mills, dredge buckets, railroad frogs, etc.

The Hadfield steel reported herein was obtained from the U. S. Army Ordnance Arsenal, Watertown 72, Massachusetts. The thickness was 0.055 inch, density 0.256 lbs. per cubic inch and the material was in the annealed condition. This steel is understood to be surplus from the World War II era; and, although manufacturing data and heat identification are not available, it is understood to have been purchased to Specification MIL-A-13259 (ORD). It should be noted that Hadfield steel sheet of relatively light gauges is not readily available in peacetime since the only known use of a light gauge material is by the Army for helmets. The U. S. Army Ordnance Arsenal, Watertown, is presently the only known source of processed material.

EXPERIMENTAL METHODS

Instrumentation for Missile Velocity Measurements

The instrumentation used in the measurement of projectile velocities consists essentially of two major components: (a) two photoelectric-type detecting screens set a known distance apart to detect the passage of the projectile and (b) an electronic interval counter-chronograph which indicates the period of time required by the projectile to pass from one screen to the other.

The screens used to detect the passage of the projectiles are Potter High Velocity Lumiline screens manufactured by the Potter Instrument Co., Inc., Great Neck, New York. These screens contain a light source, photomultiplier tubes, amplifier and output circuits. The action of the screens is such that passage of the projectile through the plane of light falling upon the photomultiplier tube, by decreasing the light intensity, produces an electrical impulse in the output circuit of the photomultiplier tube. Following the photomultiplier tube are three stages of amplification which serve to raise the signal level generated by the phototube to a value sufficient to trigger the output signal. A thyratron discharge circuit comprises the output and supplies a positive pulse of approximately 80 volts to the chronograph.

The Potter Counter Chronograph consists of a power supply, gating circuit, counting circuits, and crystal-controlled oscillator that emits a continuous train of pulses, with an accuracy of several parts per million, to the counting circuits through a gating circuit. The pulse from the output of the first detecting screen electrically opens the gating circuit, thus directing the oscillator pulses to the counting circuit. The counting circuits continue to receive and record the pulses until the impulse from the output of the second screen closes the gating circuit and terminates the counting action. The counting circuits consist of decades of multivibrators which register the time period on the face of the chronograph by means of lighted neon bulbs.

The average velocity ("instrumental velocity") of the projectile in traversing the distance between the light planes of the two screens is calculated by dividing the time registered by the chronograph into this distance.

Correction was made for the reduction in velocity of the missile incurred as a result of air retardation in traversing the distance from the midpoint of the screen system to the target. This correction was based on flight characteristics of the .22 caliber T37 fragment simulating projectile previously determined in the Center's ballistic range.[5] The drag coefficient values and the equation used to calculate velocity at the target are shown by the following equation:

$$V = \frac{d}{t}(1 - kxe)$$

Where V = velocity at target, feet per second
d = distance between screens, feet
t = time for projectile to travel distance d (time recorded by chronographs), seconds
$\frac{d}{t}$ = "instrumental velocity"
x = distance between midpoint of screens and target, feet
e = air density (assumed to be unity)
k = drag coefficient (varies with velocity as follows):

k	Velocity, feet per second
0.0028	700
0.0033	800
0.0038	900
0.0043	1000
0.0048	1100
0.0050	1150
0.0053	1210
0.0055	1300
0.0055	above 1300

V_{50} Ballistic Resistance Limit

The V_{50} ballistic test method, as used to evaluate nylon armor fabrics for acceptance, was followed. This method is fully described in Appendix B of this report. The diagram in Figure 1 shows the equipment arrangement for determining V_{50} ballistic resistance limits and missile velocity loss data. Typical operating distances between elements are 2-1/2 feet between screens, 2-1/2 feet between the target and the nearest screens, and 4 to 6 feet between the gun and the first screen. This method of ballistic evaluation determines the velocity at which there is a 50 per cent statistical probability of the armor defeating the impacting missile.

Energy Absorption

The energy absorbed by a material in retarding a missile passing through it was assumed to be equal to the loss in kinetic energy of the missile. Pairs of lumiline screens were installed in front of and behind the target material in order to determine the velocity of the missile before and after penetration. The missile kinetic energy loss was calculated from measurements of the striking and residual velocities of the missile and is equal to the product of one-half the weight of the missile and the difference in the squares of the striking and residual velocities (assuming no change occurs in the weight of the missile).

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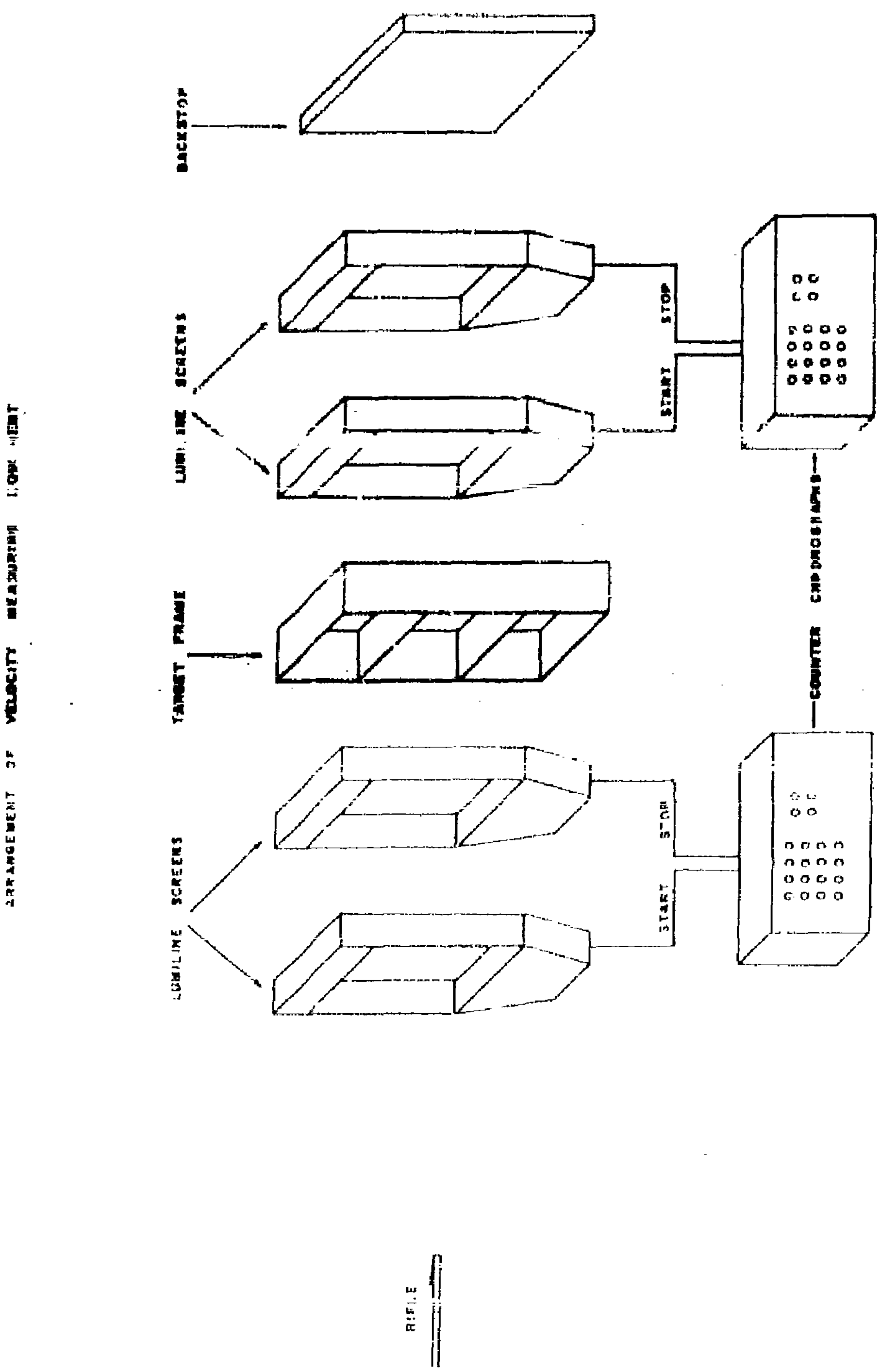

Figure 1. Arrangement of velocity-measuring equipment

The energy divided by the areal (surface) density of the material, when plotted as a function of the striking velocity, enables comparisons to be made between materials of different areal densities. The energy absorption (missile kinetic energy loss) divided by the areal density of the material is expressed as grains times ft.^{2}/sec.^{2}/oz. ft.^{2}

Test Samples

The size of test samples for most materials tested was approximately 12 x 15 inches and mounted in a frame facing the gun. Three clamps on each of the vertical (12-inch) sides held the material firmly in the frame during firing. Individual firings were spaced at two-inch intervals on the test material by moving the frame in either a lateral or vertical direction. In cases where the sample size was approximately 12 x 12 inches (some of the metals), one side was held in the target frame by the three side clamps and the other side was held by a metal bar and two clamps. The sample size used for window glass and Plexiglas was three-inch square. These squares were held in a metal frame with twelve openings 2-3/4 x 2-3/4 inches. Rubber gasketing around each opening was used to hold the squares. This frame was clamped in the target frame in the same fashion as the 12 x 15 inch samples.

The areal (surface) density determinations of the textile fabrics were made by weighing two-inch die-cut squares in an analytical balance. The areal densities of metallic and plastic materials were determined by weighing the test panel to 1/8 ounce and measuring its length and width to 1/32 inch. Thickness of samples (except for fabrics) was measured to 0.001 inch by a micrometer or dial gauge thickness indicator.

Test Projectile and Gun

All ballistic testing was carried out with the .22 caliber, 17 grain fragment simulator. A sketch of this projectile is shown in Appendix B. This projectile was fired by .22 caliber rifles: a U. S. Springfield Armory M1922 M2 was used in the velocity range up to approximately 2200 feet per second and a Winchester Model 43 Hornet was used in the range of 2200 to 4000 feet per second. The rifles, with the stocks removed, were held by a split-collar arrangement rigidly mounted on a supporting table.

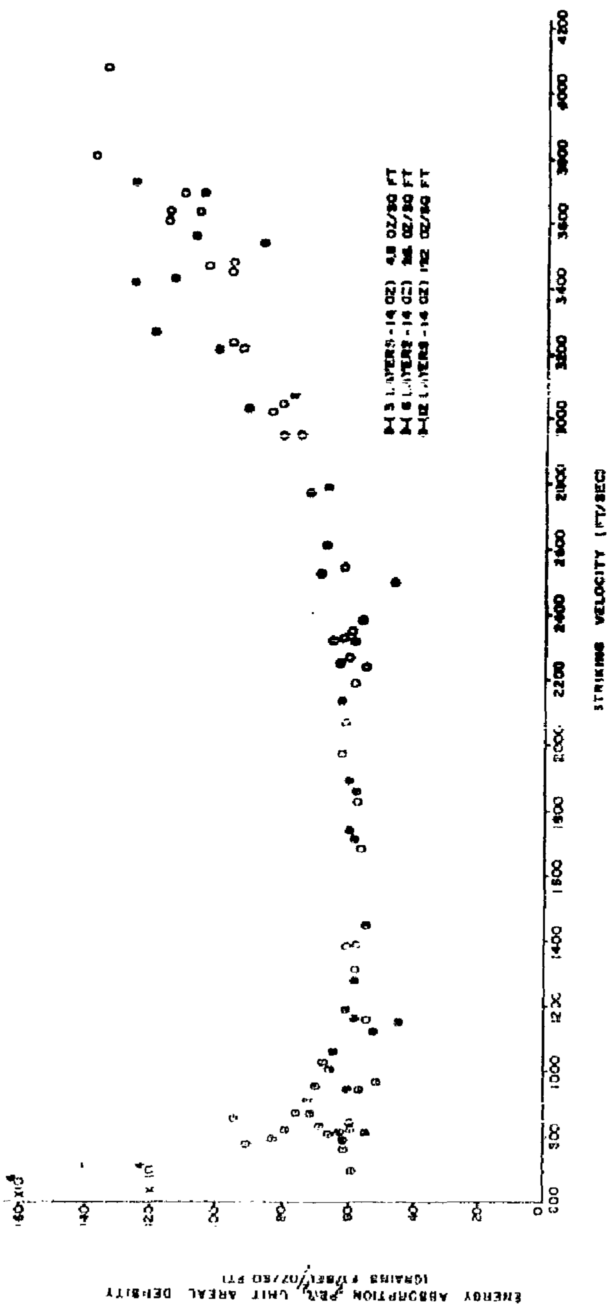

Figure 2. Relationship of energy absorption per unit areal density to striking velocity;

NYLON FABRIC

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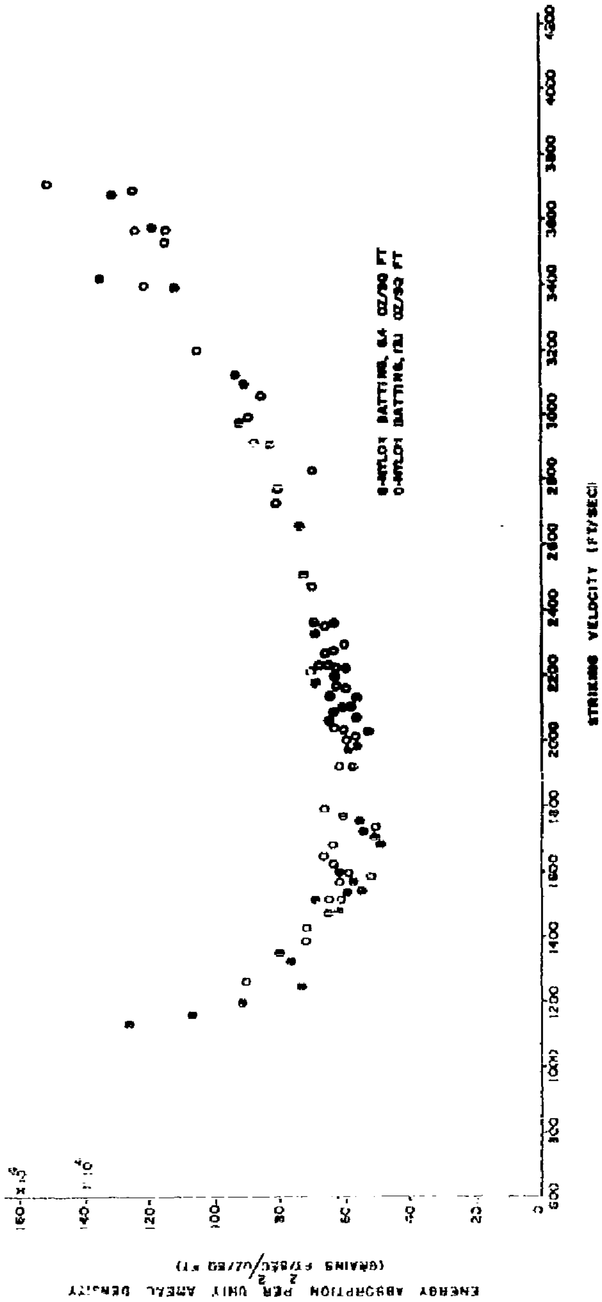

Figure 3. Relationship of energy absorption per unit areal density to striking velocity:

NYLON BATTING

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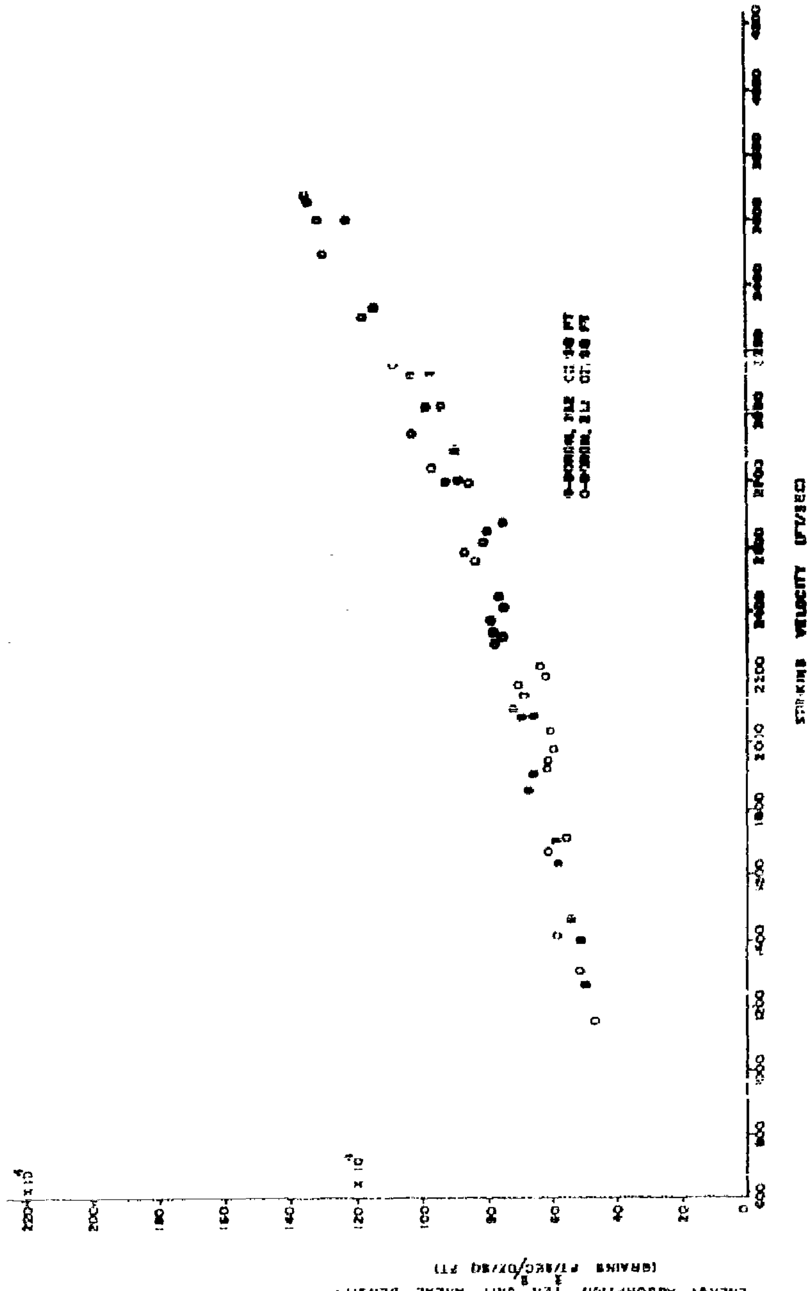

Figure 4. Relationship of energy absorption per unit areal density to striking velocity: DORON

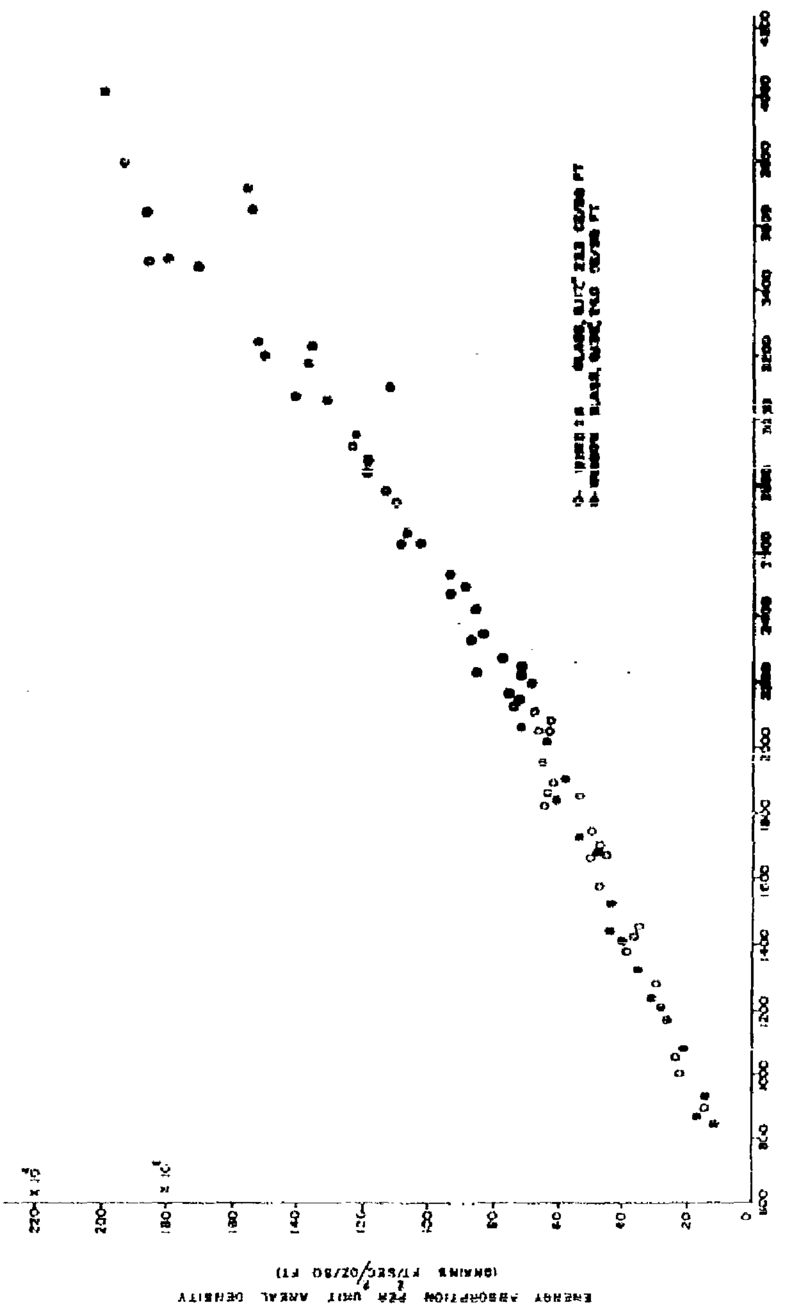

Figure 5. Relationship of energy absorption per unit areal density to striking velocity:

GLASS

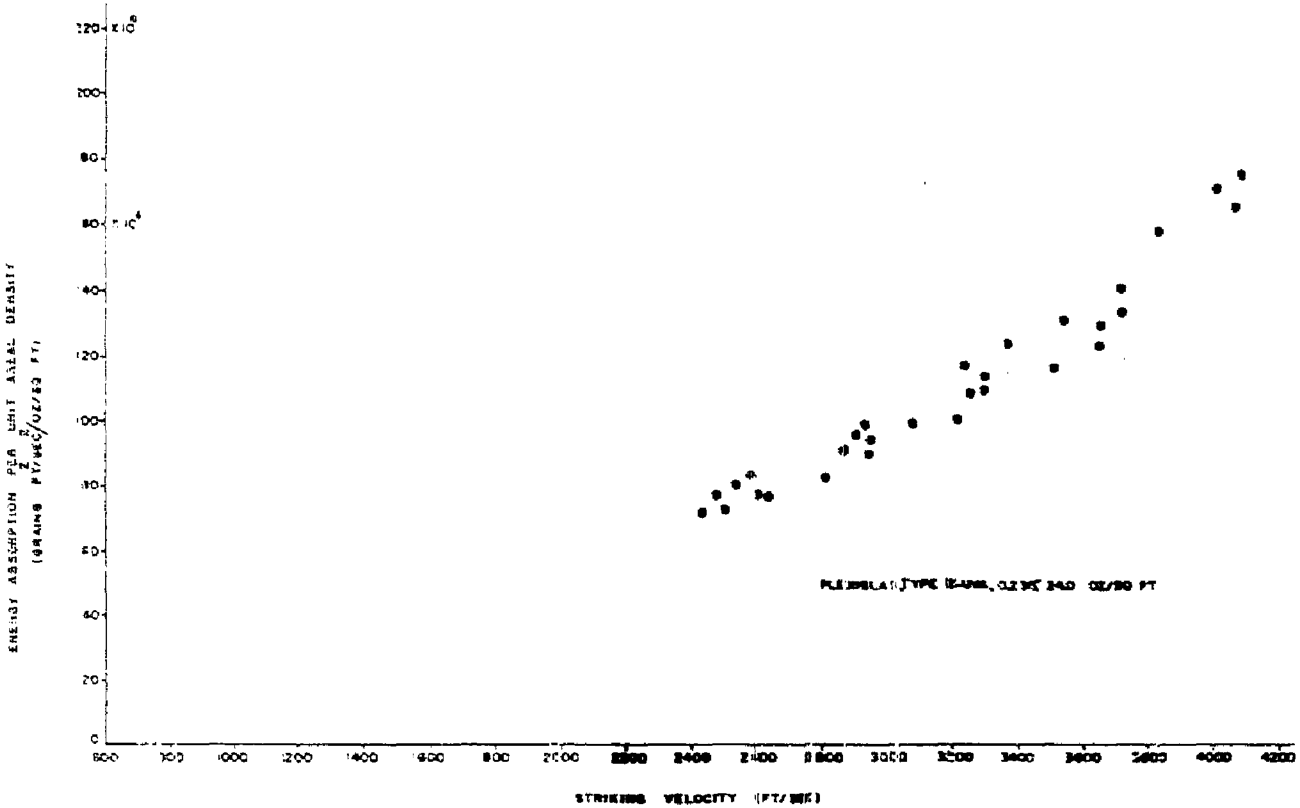

Figure 6. Relationship of energy absorption per unit areal density to striking velocity: PLEXIGLAS

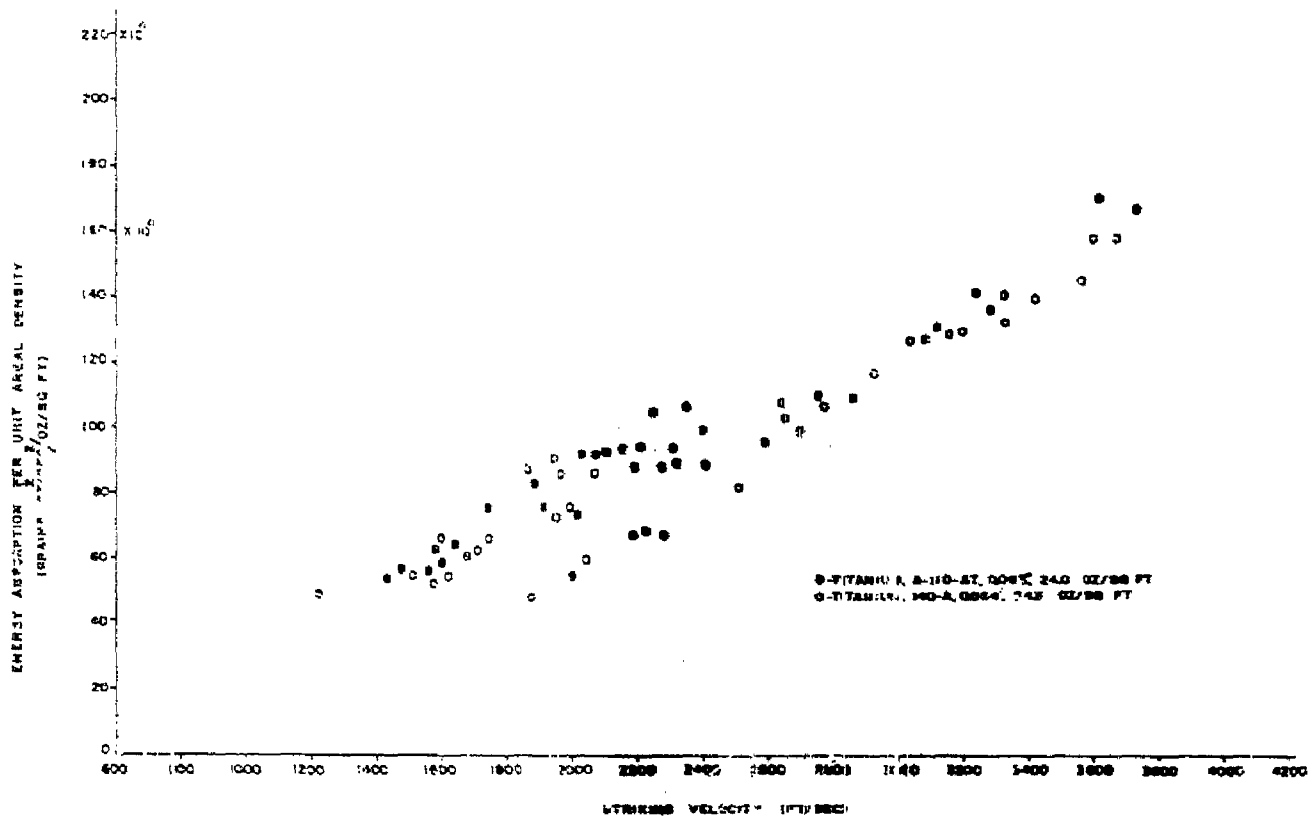

Figure 7. Relationship of energy absorption per unit areal density to striking velocity: TITANIUM ALLOYS

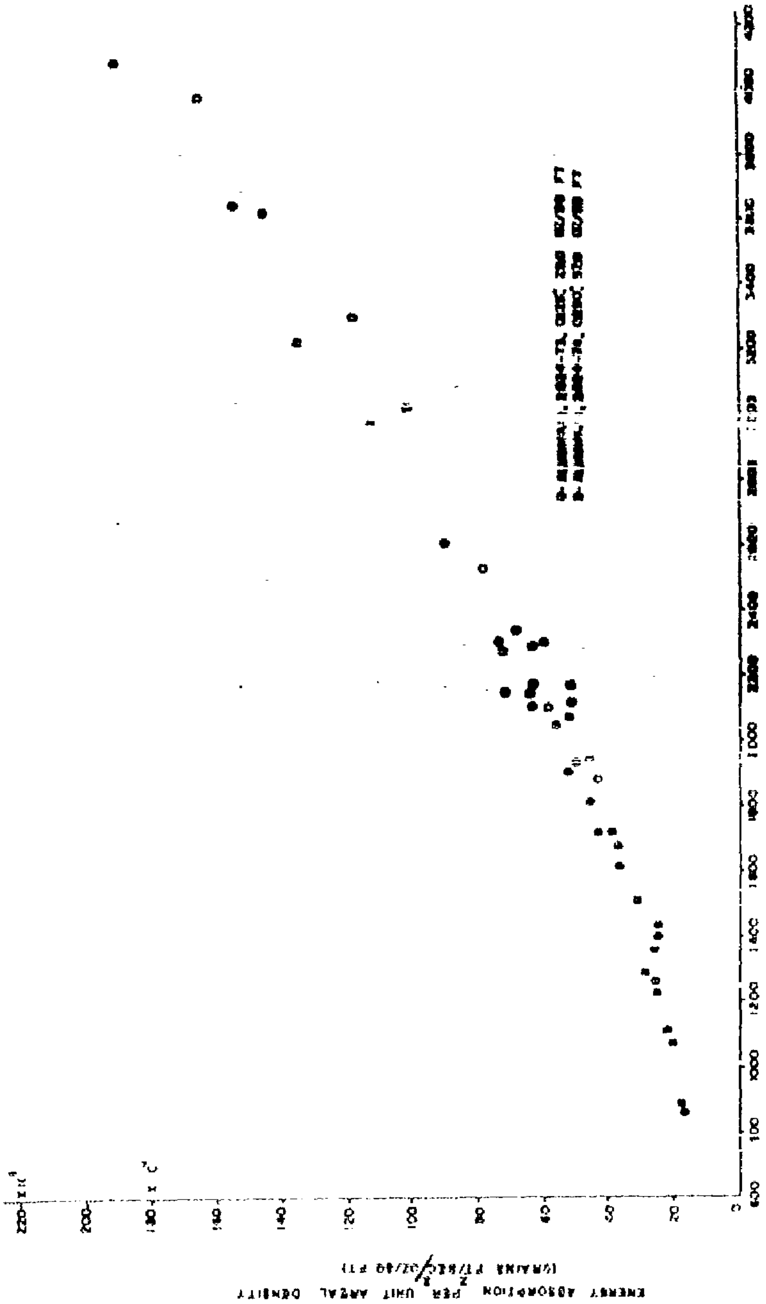

Figure 8. Relationship of energy absorption per unit areal density to striking velocity:

ALUMINUM ALLOYS

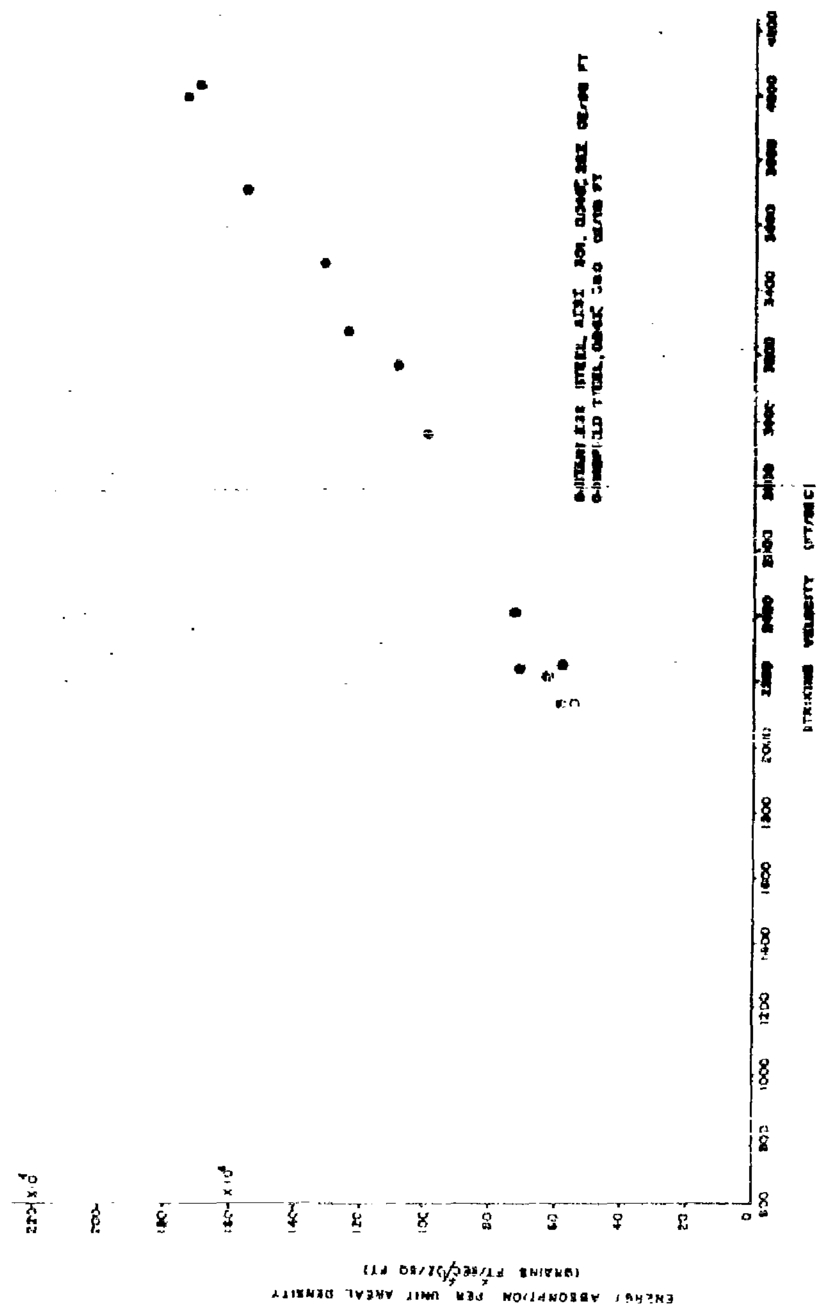

Figure 9. Relationship of energy absorption per unit areal density to striking velocity.

RESULTS

The results are presented in graphical form as Figures 2 through 11. The first eight graphs present the individual results for each valid round with the energy absorbed (loss of missile kinetic energy) divided by the areal density of the material plotted against the missile-striking velocity. Figure 10 shows nine curves representing the individual materials plotted in the same fashion. Figure 11 shows curves of V_{50} ballistic resistance limits vs. areal density for four of the nine materials reported upon herein. These were taken from Aberdeen Proving Ground data.(6) Superimposed on Figure 10 are individual V_{50} ballistic resistance limits obtained for the materials used in the energy absorption tests.

The degree of scatter indicated in Figures 2 through 9 is not uniform for all nine materials. Nylon fabric and the titanium alloys show greater scatter than the other materials. The region of high scatter for the titanium alloys appears to be confined to the striking velocity range of 1800 to 2400 feet per second. Some possible causes of scatter are:

a. Non-homogeneity of material (e.g., a woven fabric structure may not have the same number of yarns struck each time by a missile)

b. Error in calculated velocities due to change in drag coefficient as the result of missile deformation. Extensive missile deformation was noted in the case of glass, titanium alloys and Hadfield steel; no deformation was produced by the other materials.

c. Error in calculated velocities due to premature triggering of screens by armor fragments. Missile impact produced armor fragments to some degree for all materials except nylon fabric, nylon batting and Doron. Numerous fragments were produced upon all impacts with glass and Plexiglas. A cylinder was punched out of the aluminum alloys with each round fired. In the case of the titanium alloys, stainless steel and Hadfield steel, the tendency was for the metal to petal, i.e., the impacted area, deforming to the rear, tore into several sections but remained attached to the sheet. However, "petals" were ejected very often from the titanium alloys and stainless steel sheets and infrequently from the Hadfield steel. Prior work conducted with lightweight materials placed in back of the target materials to "filter out" the armor fragments showed that the energy absorption characteristics obtained with and without the "filters" were the same. Results for individual rounds which were obviously erroneous (attributed to premature screen triggering) were discarded. Only a small number of such results were obtained.

The use of the ratio of energy absorbed to the areal density instead of energy absorbed appears to reduce the results to a common basis regardless of areal density, since the results for the same material tested in different areal densities appear to be the same. (See Figures 2 and 3 for nylon cloth and nylon batting.) This ratio's apparent independence of areal density will be further investigated.

The energy absorption per unit areal density varies with striking velocity for all materials. Figure 10 shows that the shape of the curves are, to varying extents, concave upwards except for the linear relationships plotted for Hadfield and stainless steels. Two materials show minima (nylon fabric and nylon batting). T[illegible] most effective energy absorbers at the lower end of the velocity range standard (below 1600 feet per second) are nylon batting and nylon fabric. The batting is distinctly superior to the fabric at low velocities, equivalent at about 1700 feet per second and only slightly superior at higher velocities. In the intermediate velocity range of 1600 - 2600 feet per second, the titanium alloys are the best materials evaluated. Above 2600 feet per second, glass is the best energy absorber. Extrapolation of the curves beyond 4000 feet per second indicates that additional crossing of the curves may occur and that nylon batting, aluminum 2024 and Plexiglas II-UVA may be among the best energy-absorbing materials.

The V_{50} ballistic resistance limits for the nine materials are plotted on Figure 11 which also shows V_{50} ballistic resistance limits vs. areal density curves for four of the nine materials. (All V_{50} limits shown are for the .22 caliber T37 fragment simulator.) Of the four materials, the observed V_{50} limits for the aluminum alloys and Hadfield steel fall slightly above the curves representing the Aberdeen Proving Ground data. A comparison of the four curves shows that, over the areal density range of 10 to 60 ounces per square foot, aluminum 2024-3 is distinctly inferior to the other three. Hadfield steel approaches Doron and nylon fabric at about the middle of the areal density range. Nylon fabric is better than Doron below 36 ounces per square foot; Doron is better above this areal density. Nylon batting is slightly better than nylon fabric. (Two V_{50} limits of 1073 and 1016 feet per second for an areal density of 6.4 ounces per square foot are not shown by Figure 11.) Stainless steel 301 is intermediate between Hadfield steel and aluminum at the one areal density shown. Titanium alloy Ti-140A at 24.5 ounces per square foot has a V_{50} limit approximately equal to that of nylon fabric. Titanium alloy A-110AT is inferior to nylon fabric at 24.0 ounces per square foot. Plexiglas II-UVA has a V_{50} limit at 24.5 ounces per square foot approximately equal to that of aluminum 2024-T3 and 2024-T4. Glass has a very low V_{50} limit of 392 feet per second at an areal density of 26.0 ounces per square foot (not shown on Figure 11).

Materials that have high ballistic resistance limits and high energy absorption (somewhere within the areal density and striking velocity ranges studied) are nylon cloth, nylon batting and the titanium alloys. Glass is a material with an exceptionally low V_{50} limit but high energy absorption.

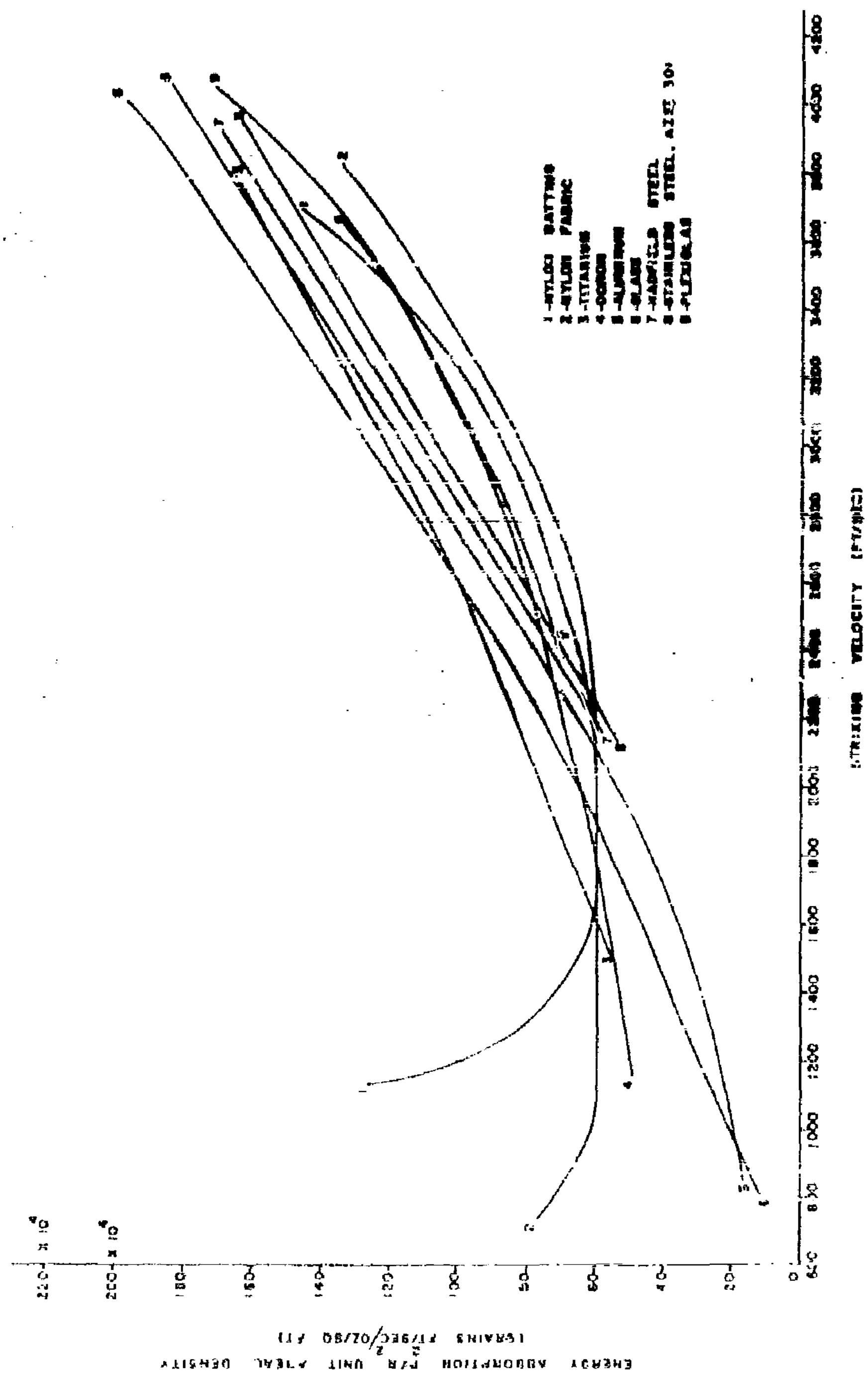

Figure 10. Energy Absorption of Armor Materials for Caliber .22, 17 Grain Fragment Simulator

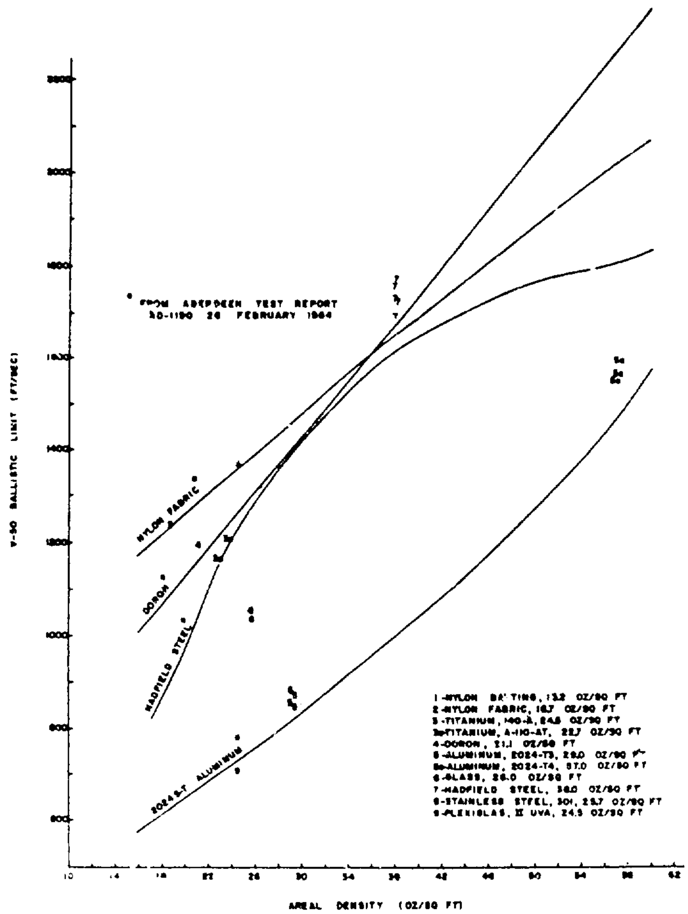

Figure 11. V_{50} Ballistic Limit of Armor Materials for Caliber .22, 17 Grain Fragment Simulator

The three most effective energy absorbing materials are well suited as components in composite armor since each material is most effective over different portions of the missile velocity range. Titanium alloys, glass and nylon textile materials will be tested in two- and three-component systems to determine combinations that are more effective than single materials. To obtain optimum ballistic resistance characteristics in armor, each component, according to the present concept of composites, must be selected and positioned so that it opposes the missile in the velocity range where it is the most effective missile-retarding material. For example, by reference to Figure 10, if the missile to be stopped has a velocity of 2000 feet per second, the components selected would be a titanium alloy positioned in front and nylon batting in the rear of a composite.

The proportion by weight of each component in a composite system can be approximated from energy absorption data by calculating: (1) the amount of the front component required to reduce the striking velocity of the missile to the velocity where the energy absorption curves for it and the adjacent component material intersect, (2) the amount of the intermediate components, in the same manner as the front component using the reduced missile velocity as the striking velocity for this component, and (3) the amount of the rear component required to reduce the missile velocity to zero.

Tests to verify synergistic effects and component weight proportions of composites will include V_{50} ballistic resistance limits and energy absorption determinations. The results of these tests will be reported in the near future.

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ACKNOWLEDGEMENTS

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APPENDIX A

PROPERTIES OF MATERIALS

Titanium Alloy A-110AT

Chemical Composition	As Specified in MIL-T-009046(ASG)(a)	Rem Cru(b)
Aluminum	4.0 - 6.0	4.6
Tin	1.5 - 3.5	2.7
Iron	0.20 Max.	
Carbon	0.10 Max.	0.10
Nitrogen	0.070 Max.	0.06
Hydrogen	0.0175 Max.	0.0148
Oxygen	0.20 Max.	
Other	0.80 Max.	
Titanium	Remainder	

(a) Military Specification MIL-T-009046(ASG) Titanium Alloy, Sheet and Strip.

(b) Rem-Cru Titanium, Inc., Midland, Pa. certified analysis.

Mechanical Properties	As Specified In MIL-T-009046(ASG)(a)	Rem-Cru(d)	Typical (c)
Tensile strength (PSI)	120,000 Min.	136,000(b)	125,000
Yield strength (PSI) (.2% offset)	110,000 Min.	132,000(b)	120,000
Elongation (%)	10 Min.	17.5	18
V Notch Charpy Impact			
ft-lb at 75°F.			19
ft-lb at -40°F.			16
Hardness (Rockwell C)			30 - 35

Footnotes on next page.

(a) The minimum difference between ultimate tensile strength and yield strength shall be 10,000 PSI.

(b) It will be noted that the material does not meet the minimum difference of 10,000 PSI between tensile and yield strength.

(c) Rem-Cru Titanium, Inc., Midland, Pa.

(d) Rem-Cru certified tests.

Titanium Alloy Ti-140A

Chemical Composition	As Specified In MIL-T-009046 (ASG)(a)	Naval Gun Factory Analysis(b)
Iron	1.0 - 2.5	1.96
Chromium	1.0 - 2.5	1.72
Molybdenum	1.0 - 2.5	1.95
Carbon	0.20 Max.	0.06
Nitrogen	0.70 Max.	
Hydrogen	0.0150 Max.	
Oxygen	0.20 Max.	
Others	0.80 Max.	
Titanium	Remainder	

(a) Military Specification MIL-T-009046(ASG) Titanium Alloy, Sheet and Strip.

(b) See Section Materials Tested.

Mechanical Properties	As Specified In MIL-T-009046 (ASG)(a)	Naval Gun Factory Tests (b,c)	Typical (d)
Tensile strength (PSI)	120,000 Min.	146,000 L- 148,000T	130,000 - 150,000
Yield Strength (PSI) (.2% offset)	110,000 Min.	136,800 L- 139,800T	120,000 - 135,000
Elongation (%)	10 Min.	14.5 L- 12.5T	12 Min.
V Notch Charpy Impact:			
ft-lb . at 75°F.			22
ft-lb . at -40°F.			18
Hardness (Rockwell C)			30-34

(a) The minimum difference between ultimate tensile strength and yield strength shall be 10,000 PSI.
(b) It will be noted that this material does not meet the minimum difference of 10,000 PSI between tensile and yield.
(c) L = longitudinal T = transverse.
(d) Titanium Metals Corp., New York, New York.

Aluminum Alloy 2024-T4

Chemical Composition	As Specified In QQ-A-355(a)
Magnesium	1.2 - 1.8
Copper	3.8 - 4.9
Manganese	0.3 - 0.9
Chromium	0.10 Max.
Iron	0.50 Max.
Silicon	0.50 Max.
Zinc	0.25 Max.
Others (each)	0.05 Max.
Others (total)	0.15 Max.
Aluminum	Remainder

(a) Federal Specification QQ-A-355 Aluminum Alloy (24S), Plate and Sheet.

Mechanical Properties	As Specified In QQ-A-355	Typical(a)
Tensile strength (PSI)	64000 Min.	68,000
Yield strength (PSI) (.2% offset)	40000 Min.	48,000
Elongation (%)	12 Min.	20
V Notch Charpy Impact		
ft-lb . at 75°F.		12
ft-lb . at -105°F.		12

(a) Metals Handbook, American Society for Metals, 1948.

Aluminum Alloy 2024-T3

Chemical Composition
(Same as 2024-T4)

Mechanical Properties	As Specified In QQ-A-355(a)	Typical(b)
Tensile strength (PSI)	64000 Min.	70000
Yield strength (PSI) (.2% offset)	42000 Min.	50000
Elongation (%)	17 Min.	18
V Notch Charpy Impact		
ft-lb at [illegible]°F.		[illegible]
ft-lb at -100°F.		12

(a) Federal Specification QQ-A-355 Aluminum Alloy (24S), Plate and Sheet.

(b) Metals Handbook, American Society for Metals, 1948.

AISI 301 Corrosion Resisting Steel

Chemical Composition	As Specified In QQ-S-00766 (Navy BuShips)(a)	Typical (b)
Carbon	0.15 Max.	0.08 - 0.20
Nickel	6.00 Min.	6.00 - 8.00
Chromium	16.00 Min.	16.00 - 18.00
Manganese	2.0 Max.	2.00 Max.
Silicon	1.00 Max.	1.00 Max.
Phosphorus	[illegible] Max.	0.040 Max.
Sulfur	0.035 Max.	0.030 Max.

(a) Interim Federal Specification QQ-S-00766 (Navy BuShips) Steel Plates, Sheets and Strip - Corrosion Resisting.
(b) Republic Enduro Stainless Steel Handbook, Republic Steel Corp., Cleveland, Ohio.

Mechanical Properties	As Specified In QQ-S-00766 (Navy BuShips)(a)	Typical (a)
Tensile strength (PSI)	75,000 Min.	90,000
Yield strength (PSI) (0.2% offset)	--	40,000
Elongation (%)	50 Min.	50
Hardness (Rockwell B)	94 Max.	85
Keyhole Notch Charpy Impact		
ft-lb at 75°F. to -40°F.	--	62-92 (approx.)

(a) Republic Enduro Stainless Steel Handbook, Republic Steel Corp., Cleveland, Ohio.

Hadfield Steel

Chemical Composition	As Specified In MIL-A-13259(ORD) (a)
Carbon	1.20 - 1.50
Manganese	12 - 15
Silicon	0.55 Max.
Phosphorous	0.08 Max.
Sulfur	0.04 Max.

(a) Military Specification MIL-A-13259 (ORD) Armor, Sheet and Strip, Steel, Rolled, Non-Magnetic; For Helmets and Other Armor Requirements.

Mechanical Properties	Typical (a)
Tensile strength (PSI)	131,000 - 142,000
Yield strength (PSI)	50,000 - 60,000
Elongation (%)	40 - 60
Reduction area (%)	35 - 50
Hardness (Rockwell B)	85 - 93
V Notch Charpy Impact	
ft-lb at 75°F.	90 - 150

(a) Metals Handbook, American Society for Metals 1948. (Applicable to 1-inch rounds.)

NOTE: The Quartermaster R&E Command plans to perform chemical analyses and mechanical property tests on metals as a general procedure in the future. Facilities to perform the analyses were not completed at the time this report was assembled.

APPENDIX B

TEST METHOD FOR V_{50} BALLISTIC RESISTANCE LIMIT*

Ballistic Limit. The ballistic limit, V_{50} in feet per second, expresses the performance of armor in resisting penetration of ballistic missiles. The V_{50} limit is the calculated velocity of the test projectile at which the probability exists that fifty per cent of the projectiles will completely penetrate the armor and that 50 per cent of the projectiles will be stopped or defeated by the armor. A complete penetration occurs when a test projectile passes through the test panel and makes a hole in a witness plate behind the test panel. A partial penetration, which is a defeat of the missile, occurs when the test projectile either is stopped by the test panel or passes through the test panel but does not make a hole in the witness plate.

Test Projectile. The test projectile shall be the caliber .22 T37 fragment simulator (see Figure 12). The test projectiles shall be segregated into classes on the basis of flange diameter with measurements made to 0.001 inch. All testing on one panel shall be limited to one size of projectile.

Firing of Test Projectile. The gun and auxiliary equipment supplies (cartridge cases, wadding, propellent, weighing equipment, etc.) utilized in the firing of the test projectile shall permit the firing of the test projectile at approximately the velocity selected for each round. Propellent shall be weighed to 0.1 milligram.

Distance and Time Measuring Equipment and Methods. Equipment and the method used to determine distances (between observation points and test panel target) shall be accurate to 1/16 inch. Equipment and method used to determine time required for the projectile to travel from the first observation point to the second (to determine velocity of projectile) shall be capable of accurate measurement to 0.01 millisecond.

Witness Plate. The witness plate shall be a 0.020-inch thick sheet of 2024-T4 aluminum alloy placed six inches behind and parallel to the test panel.

Method. The ballistic test is conducted in such a manner so as to obtain a sufficient number of rounds within a narrow velocity range and with partial penetrations alternating with complete penetrations. The first round is loaded with an amount of propellent sufficient, from prior experience, to result in a projectile velocity approximately that of the V_{50} ballistic limit specified for the material. If the first round results in a complete penetration, load the second round with slightly less propellent to produce a slightly lower projectile velocity

*Extracted from Specification MIL-C-12369B, Cloth Nylon, for Armor, dated 11 September 1957.

in an attempt to obtain a partial penetration. If the first round results in a partial penetration, load the second round with slightly more propellent to produce a slightly higher velocity in an attempt to obtain a complete penetration. Continue testing using this up-and-down method (up on a partial penetration and down on a complete penetration) until a sufficient number of complete and partial penetrations have been obtained to permit the calculation for ballistic limit, V_{50}.

Calculations. The V_{50} limit for each test panel shall be the average of the velocities recorded for ten fair impacts consisting of the five lowest velocities recorded for complete penetration and of the five highest velocities recorded for partial penetration provided the spread for the ten velocities used is not greater than 125 feet per second. In cases where the spread is greater than 125 feet per second, the V_{50} limit shall be the average of fourteen fair impact velocities consisting of the seven lowest complete penetration velocities and of the seven highest partial penetration velocities. All velocities used in these calculations shall be striking velocities calculated at the point of initial contact with the test panel. The value of the test projectile drag coefficient used in the striking velocity calculation shall be that determined by the Ordnance Corps. A fair impact results when an unyawed projectile strikes an unsupported area of the test sample at a distance of at least two inches from the edge and from any other point of impact. The V_{50} limit for the lot shall be reported as the average of all panels tested from the lot.

NOTE: An example of test equipment and operating procedures is given by the Aberdeen Proving Ground report dated 1 April 1953, with revisions, "Operating Procedure for the Ballistic Acceptance Testing of Vest, Armor, M52-3A and Similar Materiel with Projectile, Fragment Simulator Caliber .22 T37."

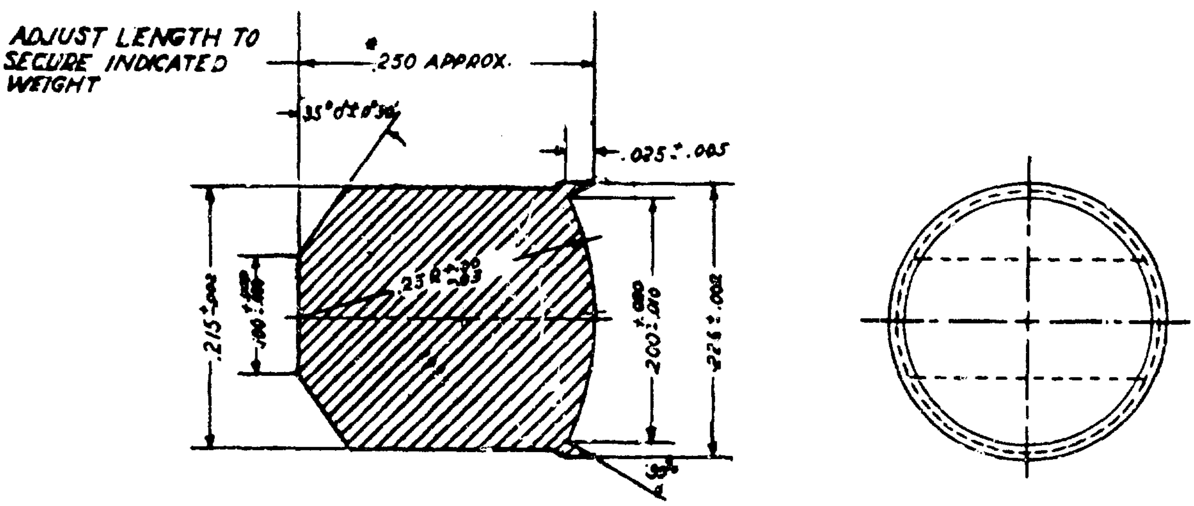

Figure 12. Caliber .22 T37 fragment simulator, steel 1020 Rockwell C 29-31, weight - 17.0 ± .5 grains